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ONR TROPICAL CYCLONE MOTION
RESEARCH INITIATIVE:
DATA ASSIMILATION CONSIDERATIONS FOR
FIELD EXPERIMENT ANALYSES

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The Office of Naval Research Tropical Cyclone Motion initiative is a five-year program to improve understanding of tropical cyclone motion. On 31 August-1 September 1989, a workshop was held in Monterey, California to consider the characteristics of data assimilation systems for tropical analyses. The focus is on special considerations that might apply in preparing a set of final analyses of the observations to be obtained in the Tropical Cyclone Motion field experiment during August and September 1990. The basic characteristics of the analysis grid, handling of the special experimental observations, objective analysis considerations, data assimilation procedures, inclusion of bogus observations, initialization techniques, and other considerations are summarized

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Abstract

The Office of Naval Research Tropical Cyclone Motion initiative is a five-year program to improve understanding of tropical cyclone motion. On 31 August-1 September 1989, a workshop was held in Monterey, California to consider the characteristics of data assimilation systems for tropical analyses. The focus is on special considerations that might apply in preparing a set of final analyses of the observations to be obtained in the Tropical Cyclone Motion field experiment during August and September 1990. The basic characteristics of the analysis grid, handling of the special experimental observations, objective analysis considerations, data assimilation procedures, inclusion of bogus observations, initialization techniques, and other considerations are summarized

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1. Introduction

A five-year basic research program to improve the understanding of tropical cyclone motion began 1 October 1986 under the sponsorship of the Office of Naval Research Marine Meteorology Program (R. F. Abbey, Jr., Program Manager). This program involves theoretical studies, analysis of existing observational data, and a field experiment in the western North Pacific region during summer 1990. A series of workshop reports (Elsberry 1986; 1987a; 1987b; 1988a; 1988b: 1989) describe respectively: the planning of theoretical studies; possible observing systems for tropical cyclone studies; a reassessment of the program in view of elimination of aircraft reconnaissance in the western North Pacific during 1987; a review of first-year progress and tentative hypotheses; a review of mid-year progress and the hypotheses, and formation of tentative working groups; and planning of the field experiment. An update of the progress and plans as of January 1989 is given by Abbey and Elsberry (1989) in the preprint volume of the 18th Conference on Hurricanes and Tropical Meteorology of the American Meteorological Society (AMS).

A workshop was held in Monterey, California on 31 August - 1 September 1989 to consider the data assimilation systems that presently exist for guidance in preparing the final analysis of the field experiment in the western North Pacific during August and September 1990. A list of attendees is given in Appendix A. We continue to benefit from the participation of cooperating agencies, such as the National Meteorological Center and the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanographic and Atmospheric Administration (NOAA). Mr. Atsushi Baba of the Japan Meteorological Agency was an invited participant. Unfortunately, Dr. Lance Leslie of the Australian Bureau of Meteorology was unable to attend because of travel difficulties, but Dr. Greg Holland ably represented that group. Bob Falvey of the Joint Typhoon Warning Center (JTWC) in Guam provided inputs regarding data availability and analysis/forecast considerations. Presentations by these various groups of their analysis, data assimilation, initialization and forecast systems contributed much to the discussion.

2. Structure of workshop

The agenda for the workshop is provided in Appendix B-1. The overall objective of the workshop was to explore the factors to be considered in preparing the final analyses based on the field experiment data set. Analysis and forecasting in the tropics has always been difficult because of the sparsity of data and an incomplete understanding of the dynamics of tropical circulations. The importance of the tropics to forecasting midlatitude weather beyond 72 h has been recognized by the operational centers for some time. As the horizontal resolution of the global models has improved, a problem has arisen in properly including tropical cyclones in the analyses and forecasts. Consequently, each global center has been considering the data assimilation of tropical cyclone data.

The first step in the workshop was to share recent developments in objective analyses, data assimilation and initialization systems for use in the tropics. To facilitate intercomparisons, a description of the NMC Regional Analysis and Forecast System (Appendix C) extracted from DiMego (1988) had been distributed to potential participants. Comparable descriptions were prepared by the Australian Bureau of Meteorology (Appendix D), Japan Meteorological Agency (Appendix E), Naval Environmental Prediction Research Facility (Appendix F), University of Wisconsin (Appendix G), and the Geophysical Field Dynamics Laboratory (Appendix H). A description of the Florida State University research system is given in Appendix I. As indicated in Appendix B-1, descriptions of the various systems were presented at the workshop.

One objective of the workshop was to identify special considerations that might apply in the analyses of the observations to be obtained in the ONR Tropical Cyclone Motion field experiment during 1990. The observational network as of May 1989 is indicated in Fig. 1 of Elsberry (1989). In addition to regular and special (including ship) rawinsondes, wind profiles at hourly intervals will be available from perhaps five special and four existing radar wind profilers. These observations are both an opportunity for studying mesoscale aspects of tropical circulations and a challenge for insertion in data assimilation systems. Enhanced satellite cloud-drift winds will be prepared after the experiment and added to the data set. The JTWC is arranging for more commercial aircraft reports along the flight tracks between Guam, Japan and Australia. Research aircraft availability is still uncertain, so that the amount of flight-level and dropwindsonde observations is unknown. Although Doppler radars are included in the network, no plans are being made to include those wind observations in the final analyses. The surface network will include a few drifting buoys as well. Finally, special efforts will be made to collect ship-of-opportunity observations.

The analysis of the field experiment data thus involves the combination of many types of observational systems with varying spatial and temporal resolutions and with differing accuracies. Although this problem is addressed each day by the various operational centers, special considerations apply in this case. First, the objective is to produce the best possible representation of the atmosphere, rather than the operational goal to produce the best possible numerical forecast. Second, the final analysis does not have to be done with time constraints that apply to operational centers. Although the experiences and basic procedures of the operational centers will be utilized, the final analyses will be prepared with a research version of the system that is appropriate to the domain and purposes of this field experiment.

The most important objective of the workshop was then to achieve a consensus regarding the essential characteristics of the data handling preparations, objective analysis, data assimilation system, initialization method and other related aspects for the preparation of the final analyses. Thus, the main focus of the workshop was in the discussion of issues. In recognition of the importance of the bogus vortex to operational track prediction, two presentations were devoted to this issue. First, Greg Holland described recent attempts to insert a bogus vortex in such models, and especially the NEPRF model in his collaborative research with Rich Hodur. Second, an analytical model to specify the non-symmetric flow that would be appropriate for a vortex in a barotropic model was described by Les Carr. Further discussion of this bogus vortex issue will be given later.

The discussion sessions (Appendix B-1) were grouped into topics on: (1) observations; (2) objective analysis; (3) data assimilation system; (4) bogus vortex; (5) initialization; and (6) future considerations and preparations. The specific questions that were designed to stimulate discussion of the issues are provided in Appendix B -2. These questions are numbered to correspond to the topic numbers listed above. Although the following sections generally will summarize the discussions of these topics, some characteristics of the final analysis will be discussed first.

3. Final analysis characteristics [P. Harr, Rapporteur]

As indicated in Fig. 1 of Elsberry (1989), the inner analysis domain will be between about 5 N and 40 N. Based on discussions with the ESCAP/WMO Typhoon Committee, it is desirable to extend the westward boundary to about 105 E, and have an eastward boundary of about 150 E. A Mercator grid is desirable for archiving the analyses in this tropical region. As the desired horizontal resolution in the inner analysis domain is 50 km, the grid will be about 75 points in the meridional direction and about 100 points in the zonal direction.

Considerable discussion occurred before setting the horizontal grid size at 50 km. Even though this resolution may be inadequate near the center of the tropical cyclone, the field experiment will not include adequate resources (aircraft) to monitor the inner circulation of the tropical cyclone. Because the hypotheses to be examined in the field experiment are focused on interaction with adjacent circulations, it is not necessary to observe in detail the inner core of the tropical cyclone. The distribution of rawinsonde stations in Fig. 1 of Elsberry (1989) is clearly inadequate to support a 50 km analysis. However, the combination of satellite data each 6 h, hourly radar wind profiler observations plus commercial and research aircraft data are believed to be adequate to justify a 50 km data assimilation system. An essential assumption in such a system is that a viable numerical model exists to provide a first-guess fields for the analyses and for spreading information from data-rich to data-poor areas in the domain. Nevertheless, the users of the final analyses will be well-advised to use the analyses carefully, and especially to check the data distribution maps in regions of questionable analysis features. Even with a 50 km resolution, the analysis will not realistically depict features of shorter than about 250 km.

Most of the operational centers are adopting vertical coordinate systems with about 20 levels, especially for regional models. This number of levels appears appropriate for this purpose.

Since the data assimilation systems use different coordinates in the vertical, the archiving of the fields will be done in the coordinate system at the center selected to prepare the final analyses. Conversions to other coordinate systems will be at the discretion of the user. If the analyses are archived in sigma coordinates, enough information (e.g., terrain pressure) and detailed algorithms must be provided to convert the fields to pressure coordinates.

The temporal resolution will vary depending on whether an Intensive Observing Period (IOP) has been designated. About eight such IOP's of 48 h duration are expected during the August-September period. Since all upper air stations within the domain are expected to launch rawinsondes each 6 h during an IOP, it is appropriate to produce 6-h analyses during IOP's. In the special case of a typhoon approaching the USSR ships, these ships will be launching rawinsondes each 3 h. In combination with hourly radar wind profiler observations, and perhaps research aircraft flight data and dropwindsondes, it may be appropriate to produce some 3-h analyses. Rather than a complete update cycle including an initialization of the numerical model each 3 h, these analyses might just use the 3-h forecast fields from a model to calculate analysis increments at the intermediate times between 6-h initializations. Such 3-h analyses would be of interest during periods of interaction between the tropical cyclone and an adjacent synoptic circulation. During the intervals between IOP's, analyses at the standard 12 h synoptic times generally will be adequate. If a 6-h update cycle is utilized throughout the two-month period, there may be some interest in archiving the 6-h fields as well.

In summary, the final analyses will be on a 50 km grid at about 20 levels in the vertical. During IOP's, the analyses will be produced each 6 h, and 3-h analyses may be prepared for a few selected cases where the data coverage justifies a shorter interval.

4. *Observation considerations* [P. Harr, Rapporteur]

a. Upper air soundings

Since the global data assimilation systems previously have had relatively coarse vertical resolution, the necessity for having significant-level (versus only mandatory pressure level) data from the rawinsondes has been questionable. For a high vertical resolution analysis as proposed here, significant-level data are considered essential. This is necessary for improving the upper-level analyses as well as the planetary boundary layer characterizations in the tropics.

Corrections to adjust for daytime heating of rawinsonde instruments also are important in the tropics. Unfortunately, the practices for shielding the radiosondes or making radiation corrections are not uniform from country to country. Even U.S. civilian and military stations use different instruments, so it is essential to determine the type of instrument at each site. The Asian stations generally correct for radiation influences.

b. Satellite observations

As described in Elsberry (1989), reprocessing of the satellite cloud-drift winds is planned to increase the coverage and to adjust for incorrect height assessments. Unfortunately, the Japanese Geostationary Meteorological Satellite (GMS) does not have water vapor channels and an atmospheric sounder that can be used in the height assessments. A "quick-look" data set that included all special observations would be helpful in quality-controlling the cloud-drift winds. This would assist in extracting more accurate winds on the spatial scales of 50 km desired here. The satellite data centers can use the operationally-produced analyses during the experiment as a "quick-look" set.

Another proposal being considered is a reprocessing of the Tiros Operational Vertical Sounder (TOVS) temperature profiles, which are now available with a higher resolution of about 75 km. The reprocessing could be done in two steps by first creating an initial analysis and then using this in the reprocessing of the TOVS profiles to produce the final analysis. In addition to being an expensive procedure, it is not clear that the improvement in accuracy of the TOVS profiles from the two-step approach would be justified in tropical regions. The alternative is to use operational sea-level pressures and sea-surface temperatures (SST) during the TOVS reprocessing. An accurate SST analysis is required in regions of strong gradients, such as along the

Kuroshio. The daily SST analysis on a 200 km grid by the JMA would not be expected to resolve these large SST gradients. A higher resolution upper ocean analysis in the western North Pacific will be operational at the Fleet Numerical Oceanography Center prior to the field experiment. It is unclear whether this SST analysis will be sufficiently accurate to justify reprocessing of the TOVS profiles. A final consideration is that acquiring multiple TOVS on the scale of 50 km might not be useful if they are simply combined by the objective analysis scheme into a single "super-observation." For example, the NMC system linearly combines two (or more) reports of the same type if the observations are within 1 ° lat or 1.2 ° long. and are separated in the vertical by less than 12.5 mb (except less than 25 mb for upper-level winds)

Some differences in practices for including satellite microwave soundings over land were noted among the operational centers. It appears that this is simply a residual from an earlier period when such soundings were less accurate. Since those centers that do utilize the land microwave soundings do not indicate adverse effects, the consensus was to include these soundings.

c. Special experimental data

As indicated in Section 2, the availability of the radar wind profiler observations at a number of sites is one of the unique aspects of the field experiment. None of the operational data assimilation systems described at the workshop can utilize hourly wind profiles. Only the United Kingdom Meteorological Office uses a continuous data insertion system that could use such high frequency wind observations. However, one concern is that such high-frequency winds would add considerable noise to the analyses.

Cross validations with rawinsondes have been completed to estimate the error characteristics of the radar wind profiler observations. Some attempts have been made to insert the radar wind profiler observations in numerical models. However, additional experimentation is needed. The NMC has a project (DiMego *et al.* 1989) to include the radar wind profiler observations from the 30 station demonstration network in the operational NMC models. They are planning a regional update cycle with a 3 h interval to utilize these wind profiles. In that case, the hourly profiles would probably be averaged over 3 h, which would tend to damp random errors and increase their apparent quality to the model. Results from the NMC project should be useful in the preparation of the final analyses from the field experiment observations.

Since the profilers in the western Pacific field experiment will not be in a regular array, the improper insertion of high frequency data at limited points may cause "bull's-eyes." The desire is to have the lower frequency meteorological modes propagate information into the adjacent data-sparse regions. In addition, the inclusion of more observations in the western North Pacific should improve the forecasts and thus reduce the background (first-guess) error characteristics.

It is emphasized that the hourly wind profiles have utility other than as part of the data assimilation. Penn State University has described the detailed structure of synoptic and subsynoptic systems with such profiles. The hourly wind profiles can also be used for detailed numerical model verifications. Similar studies are anticipated for the observations from the field experiment.

Another special data set will be the research aircraft flight-level data and dropwindsondes. After quality control, the dropwindsondes should be fully acceptable to the data assimilation system. The flight-level data can be averaged into "super-obs" on the scale of the grid resolution.

d. Data preparation

Each operational center has special procedures for preparing the observations for insertion into the objective analysis and data assimilation system (see Appendices C-G). A detailed intercomparison is not appropriate here. Differences among the analyses from the operational centers may occur when an isolated sounding is accepted by one center and rejected by another. Consequently, the flagging of data that are rejected may be important in interpreting the realism of the analysis. In many cases, the emphasis on the exclusion of another data type leads to a complicated interaction such that the effects on the analysis are difficult to isolate. It is unlikely that one data preparation system will be proven to be superior to the others prior to the beginning of the field experiment.

5. Objective analysis [P. Dobos, rapporteur]

Review of the descriptions in Appendices C-G indicates that objective analysis schemes have more common aspects than differences. Most centers have adopted the multivariate optimum interpolation (OI) technique, and generally the analysis is of the increments (difference between the observation and an interpolated value in a first-guess field derived from a numerical model integration). Each center has a method of limiting the influence of any particular data type while ensuring that horizontal and vertical coupling at rawinsonde stations is maintained. The horizontal and vertical correlation functions generally are similar among the centers, with more peaked functions for subsynoptic analyses relative to those for the global analyses. Nevertheless, the multivariate OI approach still produces problems in regions of large gradients or wind reversals such as near the center of tropical cyclones. If these gradients are not adequately resolved with observations on each side, the correlation functions will result in a displacement of the center of the tropical cyclone.

One variation among the multivariate OI schemes is the use of a volume approach (e.g., Appendix F) versus a gridpoint approach (e.g., Appendix C). In a truly optimum interpolation, all observations throughout the globe would be used. However, the matrix inversion that would be required is beyond the capabilities of present computers. Consequently, subvolumes may be defined and a locally optimum interpolation assumed. In the NOGAPS analysis (Appendix F) a maximum of 360 observations are allowed within subjectively drawn volumes. By contrast, the NMC (Appendix C) used a gridpoint-to-gridpoint approach. About 30 observations at the same level and adjacent levels are included at each gridpoint. A direct comparison of the volume and gridpoint approaches has not been made, so no basis exists to select one scheme over another.

Another exception to the commonality among the various operational centers is in the analysis of moisture fields. Some centers do a detailed analysis of the moisture field (usually a univariate versus multivariate) and include a moisture bogus based on satellite cloud patterns, tops, etc. In the case of the NEPRF system, no moisture analysis is presently done and the new moisture field simply is specified to be the prior 12-h forecast.

A special concern for tropical analyses is the representation of the divergent wind component. Decoupling the wind and mass fields in the deep tropics is clearly necessary to represent the strongly ageostrophic flows. However, it is unclear whether the accuracy and distribution of observations will be adequate to resolve the divergent wind components.

Each center has an automated quality control system that is based on the magnitude of the increments (departures from the first-guess field). Reports are labelled questionable (subject to manual scrutinizing) or are rejected outright if the increment exceeds specific limits in terms of previous standard deviations relative to the first-guess field. A detailed intercomparison is not appropriate, and again an accepted method of evaluating the goodness of this aspect is not available.

Perhaps the main point is that some manual intervention will be necessary in the preparation of the final analyses of the field experiment data. Although the automated system can be used to flag the questionable reports, an analyst must examine such reports and judge whether the report should indeed be rejected. Similarly, the overall validity of the analysis must be checked against observations that are known to be good, and for distortions such as misplaced centers or smoothed gradients. Such a manual intervention and evaluation requires expertise, takes time and thus is costly.

6. Data assimilation system (P. Harr, Rapporteur)

As used in this report, the concept of a data assimilation system includes an analysis-forecast cycle in which the objective analysis uses the previous forecast as the first-guess field. That is, the analysis is done on the increments of the observations relative to the model forecast field. Similarly, the quality control is based on the expected (or allowable) deviations from the forecast fields, rather than relative to some standard deviation of the total observation. Of course, the short-term model forecasts could not be used as a quality control or interpolation device unless the model initialization removed the high-frequency gravity waves and left only the slowly varying meteorological modes. Thus, the concept of data assimilation includes the objective analysis stage, the initialization stage and the forecast model. The initialization stage will be discussed in Section 8.

Although all of the operational centers use this data assimilation approach, it is useful to ask if the final analyses of the 1990 field experiment should necessarily use this approach. The alternative is to use a "static" objective analysis technique such as the familiar Cressman method, which might use the previous analysis as the first-guess field. The advantage of such an approach is that the fields will not be "contaminated" by the numerical model representation of the atmosphere. Greg Holland noted that the Australian Monsoon Experiment analyses were first prepared with a static approach. More recently, a data assimilation approach has been explored.

One advantage of a "dynamic" method such as data assimilation is that information from regions with data is propagated into data-sparse regions, which is generally the case in the tropics. A second advantage is that the vertical coupling between analysis levels is primarily based on the dynamically consistent first-guess fields. A vertical correlation function might be used in both approaches to extend the influence of an observation at one level to the levels above and below. Rather than extending the total value upwards/downwards, only the increment relative to model first-guess field is coupled to other levels in the assimilation approach. The final three-dimensional field of increments is then added to the background (first-guess) fields, which are dynamically consistent. This is a more conservative approach than spreading the entire value in a purely statistical approach to couple the observation to adjacent levels.

Nevertheless, the numerical model representation of the atmosphere may be unrealistic in the tropics, and especially in regions of large gradients. Furthermore, the initialization phase of the numerical model may not remove the gravity wave noise. Good observations that do not agree with misplaced gradients or with a noisy first-guess field may be rejected. Thus, the list of rejected observations needs to be checked. Given the status of data assimilation in the tropics, the user should not accept the final analyses without checking the veracity of these fields against good observations.

One by-product of the field experiment may be that the data set will provide adequate observations for testing and improving data assimilation techniques for the tropical regions. For example, the appropriate vertical correlation functions for the tropics may differ from the midlatitudes. This is very important because the two primary levels of observations in the tropics are at the gradient level (combination of surface reports and low-level cloud-drift winds) and near 200 mb (combination of aircraft reports and upper-level cloud-drift winds). Around the tropical cyclone, the winds at these two levels are typically in opposite directions. The analysis fields at intermediate levels then might be various combinations of the oppositely directed winds at the two primary levels. The uncertainty may be increased even more if observations are available at only one level so that the analysis is not "tied-down" at the top and the bottom.

In the present NMC (Appendix C) and JMA (Appendix E) systems, the global model first-guess fields are used for the regional model. Thus, the data assimilation is only done once for the global model and the fields are interpolated to smaller grids and domains as needed. Other than economy, the advantage of using the global fields is that the nonlinear normal mode initialization technique is effective at removing unwanted noise. Furthermore, the global model has no boundaries as in the regional forecast models, where the forecast fields are known to be more noisy. For the field experiment domain described in Section 3, it is advisable to use the global (or some large-domain regional) model fields as the boundary values in the data assimilation. However, the boundaries should be slightly larger than the domain to be archived to assure that boundary noise is reduced.

The key point is that the boundary values in the final analyses can be derived from analyses on a larger scale rather than from forecast fields. Even so, the northeastern and southeastern corners of the domain are in data-sparse regions and the uncertainty in these regions will be considerably larger.

The disadvantage of using the global model fields is the coarser resolution in the first-guess fields. If the information is to propagate correctly into data-sparse areas, the resolution in the forecast model should be the same as in the analysis. Both NMC and JMA expect to have a regional model update system in operation by August 1990.

As indicated in Section 4, the field experiment will include some new observations. Both the quality control and the weighting coefficients in the objective analysis require estimates of the expected departures from the numerical model predictions. This type of information is being gathered for radar wind profilers by comparisons with collocated rawinsondes. The NMC has a special project that is studying the incorporation of wind profiler data into the analysis system. Since the final analyses will be produced several months after the field experiment, several operational centers may have gained experience in incorporating the profiler observations that will be transmitted during the field experiment. Revisions of the coefficients can be made prior to producing the final analyses.

Representatives of the operational centers expect no difficulty in incorporating the dropwindsonde data. Special observations such as the ground-based radiometer temperature profiles are more unusual and may require "tuning" as the error characteristics are developed during the experiment.

7. Insertion of bogus observations (P. Harr and P. Dobos, Rapporteurs)

It was anticipated in the preparation of the discussion questions (Appendix B-2) that this topic would focus on the insertion of winds around the true position of the tropical cyclone, and around adjacent synoptic features such as Tropical Upper Troposphere Trough (TUTT) cells. However, the discussions at the workshop also concerned the need for a bogus of the moisture field. In his presentation, Greg Holland ranked the inclusion of a moisture bogus of tropical convective features higher than even the tropical cyclone bogus vortex.

a. Tropical cyclone bogus vortex

The dynamical tropical cyclone track prediction models generally include a bogus vortex procedure because inadequate observations exist to properly define the circulations. If observations are available on only one side of the tropical cyclone, a distortion in the circulation may occur such that the center is misplaced toward the data-sparse side. Although the need for such a bogus is accepted so that the track prediction begins from the correct location, the proper or most effective form of the bogus is not evident. A common characteristic of the dynamical track predictions is large errors (no skill relative to persistence) in the first 24 h and then rapidly improving forecasts at 48 h and 72 h (Elsberry 1987c). The desire for operational track prediction is then to define the initial circulation in the region of the tropical cyclone in such away as to start the storm in the proper location and also improve the initial motion. However, this is not the case for the production of the final analyses for the 1990 field experiment. To the maximum extent possible, the relevant consideration for the final analyses is to draw closely to the observations that do exist, and to minimize the influence of the bogus vortex. As indicated previously, inadequate observations will exist to accurately define the inner core of tropical cyclones. Thus, some bogus observations will be necessary to define the tropical cyclone circulation without obscuring the observations in the interaction zone between the tropical cyclone and the environment. Indeed, the objective of the field experiment is to observe and describe the primary physical processes in this interaction zone.

Les Carr described a quasi-analytical process for specifying the interaction flow between a symmetric tropical cyclone and the environmental flow in a barotropic model. That is, a wave number one gyre circulation is added to the symmetric bogus so that the vortex propagation is included in the initial conditions. This procedure was shown to eliminate almost all of the slow bias in the first 24 h of the forecast. However, this theory is for barotropic motion in a well-specified environmental flow. As Greg

Holland pointed out, it is often quite difficult to separate the vortex circulation from the environmental flow in nature. The relevant point here is that these asymmetric gyres extend thousands of km from the center. Imposing such gyres might improve operational track forecasts, but inserting these large-scale gyres would clearly be inappropriate for the final analyses of the field experiment. Except for the inner regions, the field experiment observations should define these gyre circulations, rather than having these circulations be inserted arbitrarily.

Given that some bogus of the inner core vortex will be necessary -- should a model spin-up or an empirical vortex structure be imposed to fill up the gaps between observations? Greg Holland suggested another alternative of imposing a maximum vorticity of about 2f - 3f at the storm center location, and then use a nudging technique so that the model physics spread the influence outward. This technique is being developed at BMRC and further details will be available later.

The NMC has used the model spinup approach so that the inserted information is consistent with the numerical model. The bogus vortex is added to a spectrally filtered field that retains only the longest 10 waves. Although it is desirable that the bogus vortex be related to the actual storm size and intensity, a full representation is *impossible on a 50 km grid.* The normal mode initialization makes the mass fields consistent with the bogus winds so that the bogus is retained during the integration. This technique is also still in development.

Until recently, NEPRF also used a model spinup vortex. A persistent bias of low-latitude tracks toward the pole was believed to be due to use of a too large vortex. Rich Hodur is now testing a minimal bogus with 13 pseudo-observations near the center, which is an empirical vortex approach.

One of the key problems is to blend the imposed inner vortex with the observations in the environment. The analysis technique should not map the small-scale gradients onto the large-scale wind field. Part of the problem is related to he large winds in the swirling circulation that tend to make the fields quasi-circular rather than rectilinear. That is, information might be advected by the swirling motion might be better represented in a cylindrical coordinate system rather than in x-y coordinates.

It seems clear from the discussion at the workshop that the treatment of the bogus vortex is still an open question. One possibility is to consider a second analysis that does not include a bogus and advise users to avoid interpretations that utilize the inner core regions with no data. If a bogus vortex is included, the user must determine how far from the storm center that the gridpoint values -e not influenced by the bogus observations. In view of these considerations, a minimal storm bogus might be desired by most users of the final analyses.

b. TUTT bogus

The rawinsonde resolution will generally not be adequate to define the structure of the TUTT cells. If the TUTT is in the climatological position of 20 - 35 N, the ship observations and radar wind profilers should improve the coverage. Since some TUTT cells are only 100 mb deep and others extend to near the surface, the key issue is how well the data assimilation system will represent the vertical structure.

Some advantage for tropical cyclone motion studies might be gained from a bogus of the adjacent TUTT cells. This might lead to a better representation of the wave number one asymmetry that is directly involved in tropical cyclone motion. The relative motion of the tropical cyclone and the bogus TUTT cell would contribute to a time-dependent wave one asymmetry. However, a researcher who wants to use the data set to study TUTT cells would rather not have a bogus inserted. Because of the uncertainties in our ability to bogus such cells, the consensus of the workshop seemed to be to avoid a bogus.

c. Moisture bogus

Greg Holland emphasized the contribution of the BMRC moisture bogus technique to the success of the AMEX analyses. Such features as the Intertropical Convergence Zones, cloud clusters and rainbands are not resolved well in the data assimilation without the moisture bogus. Atsushi Baba showed a case in which the JMA moisture bogus scheme improved the representation of the cloud features surrounding a typhoon. The JMA scheme uses infrared cloud-top temperatures observed by the Geostationary Meteorological Satellite (GMS). The NMC also has a moisture bogus technique for the eastern North Pacific region. By contrast, none of the U.S. Navy models uses a moisture analysis, although such a scheme is being explored for the global analysis.

Although the moisture analysis scheme is univariate, the field must be compatible with the mass and wind analyses. For example, regions of high moisture should not be supersaturated, and the initial moisture convergence values should be compatible with the latent heat parameterization technique. If the fields are not compatible, large amounts of heat might be released in the first time steps. Conversely, too low moisture values may delay the onset of precipitation for several hours at the beginning of each integration.

In addition to the infrared cloud top temperatures, the precipitable water values and the precipitation regions detected by microwave sensors such as the SSM/I might also be used in the moisture bogus. Unfortunately, a VAS-type instrument as on the U.S. GOES is not available on the GMS. None of the operational centers uses the precipitation observations in the moisture analysis. The Florida State University system (Appendix I) does use the precipitation distribution for enhancing the moisture fields. This labor-intensive approach will be done only for selected Intensive Observing Periods.

In summary, a moisture analysis and a moisture bogus technique that uses satellite-observed cloud tops, patterns, etc., appear to be necessary for the final analyses. The transportability or general applicability of the various moisture bogus techniques needs to be examined.

8. Initialization (P. Dobos, Rapporteur)

Initialization of the numerical prediction model that provides the first-guess fields in the data assimilation cycle is essential to remove the non-meteorological modes (spurious gravity waves). Without this step, these predicted fields during the early portion of the model integration, which are used as the first-guess fields, would contain large amplitude waves that would obscure the slowly evolving meteorological modes. Comparison of the new observations with such noisy short-term predictions would result in erroneous increments for the objective analysis and quality control steps. By contrast, the meteorological modes contain the slowly varying time tendencies that should be consistent with the new observations. Of course, the model prediction is not perfect, and the observations also contain noise. The quality control step flags or eliminates observations that deviate markedly from the first-guess. Those observations (expressed as increments relative to first-guess field) that pass the quality control test, and are within the proper horizontal and vertical distance from the gridpoint, are included in the objective analysis (Section 5).

For the operational global models at NMC (Appendix C), Bureau of Meteorology (Appendix D), JMA (Appendix E) and Fleet Numerical Oceanography Center (Appendix F), a nonlinear normal mode initialization (NNMI) is used. An adiabatic version is used at all these operational centers except JMA, which includes the physical processes. Not all the vertical modes of the numerical model are initialized, because this would remove too much of the divergence in the initial fields. For example, the initial vertical motion necessary to support the observed cloud distribution may be unestimated if too much divergence is removed. Secondary circulations that researchers are attempting to diagnose may also be damped if too many vertical modes are eliminated.

For the operational regional models at Bureau of Meteorology and FNOC, a vertical normal mode initialization is used. Only a few (say, three or four) vertical modes are initialized in this procedure. The Naval Operational Regional Atmospheric Prediction System (NORAPS) at FNOC is only initialized each 12 h. Although other centers initialize regional models each 6 h, it is not clear whether the vertical mode initialization adequately removes noise so that a 3-h initialization could be done.

Because of the limitations and uncertainties regarding NNMI in the tropics, a number of research groups are experimenting with alternate or more sophisticated initialization techniques. Most of these efforts include a dynamic initialization technique. An example is the Florida State University (FSU) version described in

Appendix I. Because the dynamical initialization involves integrating the model equations in an iterative scheme, it is more costly than the NNMI or static initialization techniques. In the FSU version, an explicit initialization of the u, v and p_s fields via a Newtonian relaxation (nudging) is combined with a physical initialization of the outgoing longwave radiation, surface heat and moisture fluxes and the cumulus convection (Appendix I). The Newtonian relaxation is used over the previous 24 h to create initial fields that are consistent with the observations and the physical processes. FSU has proposed to do several cases from the field experiment with this complex technique.

The GFDL has developed an initialization technique appropriate for hurricanes (Appendix H). In the static initialization, all terms in the divergence equation are included with bounds put on the time tendency term. A dynamic initialization option is also available, as is a moisture initialization. Y. Kurihara suggests that additional research is necessary to treat high-resolution topography during the initialization process.

Diabatic effects are included in the BMRC research version (Appendix D) via a dynamic initialization technique developed by L. Leslie. A nudging method is used to initialize the heating rates associated with convective clouds in the tropics. At CIMSS (Appendix G), an initialization is used only at the beginning of the pre-integration period. The data are then used in a nudging-type initialization during the assimilation period. According to Robert Aune, they do have to control a lot of aliasing associated with the boundary conditions in the regional model.

Although initialization techniques are available at the operational centers, this aspect of the problem might be considered as a fruitful area of research with the data set from the field experiment. A particular initialization technique will be utilized by the center selected to prepare the final analyses. However, it is likely that the testing of improved initialization techniques could lead to further refinements in the final analyses in the future.

9. Further considerations

a. Selection of final analyses center

The objective of producing final analyses for the 1990 field experiment in the western North Pacific raises a number of issues with regard to the data assimilation procedures. As is evident in the above discussion, a data assimilation system is a complex, highly interrelated system of data quality controls, objective analysis, initialization and numerical model. Each operational center has particular system features that make it difficult to demonstrate a marked superiority relative to other centers. Furthermore, the operational systems are continually being tested and improved, especially for application to regional domains. The research groups represented at the workshop are also actively pursuing improved data assimilation systems. Their efforts in dynamic initialization techniques may be particularly relevant here because of the variety of new observational systems and higher frequency data to be acquired during the field experiment. Other research on the tropical cyclone bogus or the moisture bogus procedure may also contribute to refining the data assimilation procedures.

Although it may be tempting to delay selection of a center to produce the final analyses, a decision is required to allow time for preparation prior to the experiment. Because of financial limitations, only one center can be selected. It is expected that the experiment will provide a comprehensive data set for the testing and improving data assimilation systems. Consequently, other operational centers and research groups may produce special analyses from selected periods. Thus, it may be a misnomer to refer to this set as the "final" analyses. Nevertheless, this set of analyses should be adequate for use in diagnostic studies and for numerical model studies.

b. Archiving of initialized and diagnostic fields

The initialization process is an essential step in the data assimilation to remove spurious gravity waves (Section 8). This step reduces the divergent component of the wind field and does produce smoother vertical motion fields. The question then arises whether the initialized fields should be archived as well as the "raw" wind and mass fields. Furthermore, the data assimilation procedure results in a series of derived fields such as surface fluxes, precipitation rates as a function of x, y and z, radiative fluxes, cloud distributions, etc. that might be used in diagnostic studies. Should these fields also be archived? Finally, the numerical model integrations that are used in the data assimilation cycle might be extended to produce forecast fields as well. Should such forecasts be produced and archived?

Users without access to a numerical model will desire the derived fields listed above, but they are likely to want the non-initialized fields for the diagnostic studies. Others will use only the primary fields for diagnostic studies to avoid the model-dependency that is inherent in the derived fields. To accommodate the first group, the analysis center should arrange to archive the derived fields and provide a detailed description of the model techniques that are involved.

Representatives of the potential analysis centers indicated that they did not have an interest (or capability) to produce forecasts that would be archived. This would be an expensive effort. Furthermore, the focus of the field experiment is on understanding of tropical cyclone motion, rather than on prediction *per se*. The modeling groups will produce their own forecasts.

A data archiving format called BUFR that has been developed at the European Centre for Medium-range Forecasts may become the standard format among the large operational centers. However, the format that is familiar to most diagnostic users is the FGGE data format. Consequently, it was tentatively decided to archive the screened data in the FGGE II format and the final analyses in the FGGE III format

c. Concluding remarks

In view of the more than one year between now and the preparation of the final analyses, only the basic characteristics of the data assimilation system can be described from the workshop discussions. First, the domain, horizontal and vertical grid resolutions, etc. are given in Section 3. A multivariate optimum interpolation scheme will be used to analyze the wind and mass fields, and a univariate scheme will be used for moisture. A minimal tropical cyclone bogus is to be used near the center to define the center position and to fill in the fields out to the nearest observations. A moisture bogus based on cloud tops and patterns will be an essential part of the moisture analysis. A regional model with a similar resolution as the data assimilation fields (50 km) will be used A vertical mode initialization will probably be used unless a suitable dynamical initialization procedure is available.

A more detailed description of the data assimilation system will be provided as part of the documentation of the final analyses from the 1990 Tropical Cyclone Motion field experiment in the western North Pacific. The present plan is to have these analyses available one year after the field experiment.

Acknowledgements

The representatives who prepared the descriptions of data assimilation systems (Appendices C-I) prior to the workshop are thankfully acknowledged. Their contributions, along with those of the other attendees, to the discussions were the primary factor in the success of the workshop. Ms. Lundy Elsberry assisted with the local arrangements.

Preparation of the workshop report has been supported by the Naval Postgraduate School direct research funding. Pat Harr and Paul Dobos contributed much to the report via their complete rapporteur reports. Bob Renard and Mary Jordan reviewed the manuscript, which was skillfully prepared by Ms. Joan Murray.

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Appendix A. List of Attendees

Name	Agency
Robert Abbey	Office of Naval Research
Kok-Seng Yap	Florida State University
Bill Frank	Penn State University
Yoshio Kurihara	Geophysical Fluid Dynamics Lab (NOAA)
Stephen Lord	Geophysical Fluid Dynamics Lab (NOAA)
Jim Goerss	Naval Environmental Prediction Research Facility
Ted Tsui	Naval Environmental Prediction Research Facility
Chris Hartsough	Naval Environmental Prediction Research Facility
Bob Aune	University of Wisconsin
Chris Velden	University of Wisconsin
Robert Merrill	University of Wisconsin
Greg Holland	Bureau of Meteorology Research Centre
Atsushi Baba	Japan Meteorological Agency
Bob Falvey	Joint Typhoon Warning Center
Russell Elsberry	Naval Postgraduate School
Patrick Harr	Naval Postgraduate School
Lester Carr	Naval Postgraduate School
Terry Williams	Naval Postgraduate School
Pat Jacobs	Naval Postgraduate School
Paul Dobos	Naval Postgraduate School
Melinda Peng	Naval Postgraduate School
Donald Gaver	Naval Postgraduate School

APPENDIX B-1

DATA ASSIMILATION FOR TROPICAL CYCLONE STUDIES AGENDA

31 August 1989

0845 Registration
0900 Welcoming remarks--R. F. Abbey, Jr.

Purpose of Workshop--R. L. Elsberry

Background of observations and data management plans--
R.L. Elsberry

Presentations of data assimilation systems
National Meteorological Center-Steve Lord

Bureau of Meteorology (Australia)-Greg Holland

Japan Meteorological Agency-Atsushi Baba

Naval Environmental Prediction Research Facility--
Jim Goerss

University of Wisconsin--Robert Aune

Geophysical Fluid Dynamics Lab--Yoshi Kurihara

Florida State University (K.-S. Yap)

1300 Discussion of Issues
Bogus vortex considerations--Greg Holland

An analytical bogus vortex for barotropic models--
Les Carr

Discussion topic 1--How will the types of observations in the field experiment data set affect the objective analysis and/or data assimilation system?

Discussion topic 2--What should be the characteristics of the objective analysis?

1 September 1989

0830 Discussions (continued)

Discussion topic 3--What should be the characteristics of the data assimilation system?

Discussion topic 4--What bogus vortex should be included in the final analysis?

1300 Discussions (continued)

Discussion topic 5--What should be the characteristics of the initialization system?

Discussion topic 6--What are the future considerations or needed preparations prior to the production of the final analyses?

1530 Wrap-up and final remarks

DESIRED OUTCOMES OF WORKSHOP

1. Sharing of knowledge and stimulation of interest in the objective analysis and data assimilation approaches for tropical circulations.

2. Identify special considerations that will apply in the analysis of the observations to be obtained in the ONR Tropical Cyclone Motion field experiment during 1990.

3. Achieve a consensus regarding the essential characteristics of the data handling/preparations, objective analysis, data assimilation system, initialization method and other aspects in the preparation of the final analyses for the 1990 field experiment data set.

APPENDIX B-2

DISCUSSION QUESTIONS

1-1 How will your system make use of observations from radar wind profilers? research aircraft flight data? dropwindsondes? How would your system respond to higher density cloud drift winds from a post-analysis? Would these additional observations simply be absorbed into super observations with little impact?

1-2 Would your system benefit from a reprocessing of the TOVS 75 km temperature profiles prior to the final data analysis? Would this change your quality code assignment or error standard deviations?

1-3 Should a moisture field bogus procedure such as at NMC be a part of the final analysis preparation? What special considerations should be given to humidity analyses for the field experiment data set? Or is this primarily a passive variable in the data assimilation that is highly model-dependent (latent heat of parameterization scheme)?

1-4 Since the data preparation does not have to be completed within a few hours as in operational procedures, what degree of additional monitoring of the observations by an analyst is desirable or necessary in the final analysis set?

2-1 Given the station spacing of the TCM experiment (plus likely auxiliary observations), what is the minimum horizontal and vertical resolution of the final analyses?

2-2 Is a grid-specific system such as ROI of NMC easily transportable to another region?

2-3 Since the analysis domain extends from midlatitudes to the deep tropics, how will the differing mass-wind balances be taken into account?

2-4 What analyses of variables should be univariate?

3-1 Should there even be a data assimilation? What advantages/disadvantages of the data assimilation system justify its application to a research data set (as opposaed to an operational prediction system)? Would a successive corrections technique provide just as viable (with less effort, time and cost) analysis of the tropical cyclone and its environment on the desired horizontal scales?

3-2 What boundary conditions will be utilized during the data assimilation?

3-3 What aspects of the observational and analysis system contribute to vertical coupling of the different layers? Should special consideration be given to vertical coupling in tropical circulations and especially the tropical cyclone?

3-4 What horizontal and vertical correlation functions would be appropriate for these data sets?

3-5 How will the weighting factors be established for special observations in the field experiment data set, such as radar wind profilers, reprocessed satellite cloud drift winds, dropwindsondes, etc.?

3-6 What is the impact of having the same/different forecast model in the data assimilation system for a first-guess field versus in the actual forecast? That is, what are the advantages/disadvantages of a regional update system?

3-7 What data quality flags should be assigned in the final data set?

4-1 What bogus vortex (if any) should be included in the data assimilation system for producing the final analyses of the field experiment data? Should multiple final analyses be produced with different degrees of bogussing? Can an algorithm be provided to remove the bogus for those who do not want it included?

4-2 Should a model spinup or an empirical bogus vortex be used?

4-3 Should other tropical circulations such as the Tropical Upper Tropospheric Trough (TUTT) cells also be bogussed?

5-1 What are the advantages/disadvantages of the vertical mode initialization techniques for the regional models versus the nonlinear normal mode initialization techniques for global models? Will the vertical mode initialization provide the same noise suppression during the forecast model integration to allow the forecast fields to be used in a 6-h or even a 3-h data assimilation cycle?

5-2 What is the status of diabatic initialization techniques and how might this aspect affect the final analyses in the tropics?

5-3 Would dynamic initialization techniques that incorporate estimates of the horizontal/vertical distributions of precipitation contribute significantly to the quality of the final analyses?

6-1 What research in data assimilation is likely to impact the design of the system prior to production of the final analyses during 1991?

6-2 What diagnostic fields (e.g., surface heat, moisture and momentum fluxes; convective and large-scale precipitation; etc. from the data assimilation should be archived for diagnostic studies? Should the forecasts from each IOP analysis also be produced and archived?

6-3 What logistical considerations are necessary to provide the complete field experiment data set to the center that will prepare the final analyses?

APPENDIX C

System Title: Regional Analysis and Forecast System (RAFS)

Published Description: G.J. DiMego, 1988: The National Meteorological Center Analysis System. Mon. Wea. Rev., 116, 977-1000.

Domain: Hemisphere (Northern)

Horizontal Resolution(s): Analysis: 180 x 60, 2 long., 1.5 lat. Model: 366, 183, 91 km (See Fig. 1 for thinned grid)

Vertical Resolution: 16 levels (first 12 below 250 mb) σ_p = 1000, 965, 922, 872, 816, 755, 689, 619, 547, 473, 398, 324, 251, 181, 115, 54 (same for model)

Coupling: Geostrophic wind/mass

Analysis: Multivariate OI in geopotential (h) and wind (u, v). Deviations from first-guess: up to 30 (33) observed values in first (second) analysis level; 30 values at upper levels with nearest 20 from profile, next 10 from single-level observations, and with at most two heights and one wind from a single sounding.

Characteristics: Significant level radiosonde data used. Moisture (specific humidity at first 12 levels) is univariate (12 values max). Direct calculation of layer-mean virtual temperature.

First-guess error correlation: Horizontal correlation function (see Fig. 4). Vertical correlation function (see Fig. 5)

Initialization: Nonlinear normal mode initialization of analysis increments based on the Temperaton implicit method with special hemispheric adiabatic version of operational spectral forecast model with 80 wave (rhomboidal) and 16 layers.

Super Observations: Two (or more) reports of same type combined if <1 lat.; <1.2 long; <12.5 mb except <25 mb for upper-level winds. Linear average of time, location, pressure and observed values. This procedure is performed after all quality control checks are made, and specifically after a buddy check.

Data Preparation Characteristics:

Merging of significant level data

Typical vertical resolution (25 mb when significant level)

Daytime shortwave radiation correction

Satellite T profiles: geopotential thickness between mandatory levels

No land retrievals

No microwave retrievals south of 20 N

No precipitable water info used

No VAS profiles

Moisture bogus profiles based on cloud imagery

Wind reports from conventional aircraft

Satellite cloud draft winds at reported levels

Ship, buoy and manual bogus surface reports included

Land surface pressure (also temperature and moisture, but not winds) reports included if observed within 1.5h of analysis time (other types of obs if within 3h)

Quality code assignment: Four categories (Table 4) for observations passed by automated checking procedures and monitoring analyst

Data cutoff time: 2.25 h after synoptic time

First-guess characteristics: Global data assimilation system 6-h forecast with 80-wave, 18-layer spectral model (Note: Not a regional update model. Error growth rates have been decreased recently to reflect increased confidence.)

First-guess corrections std. dev: Analysis error std. dev. plus error growth rate, except must be less than minimum allowed values (Table 5). Maximum analysis error is climatological error variance.

Wind errors: High latitudes: u, v from h via geostropic covariance model. Low latitudes: Prescribed profile of wind errors. Blend between 10 N and 25 N.

Observed corrections to first guess: Profiles: 25 mb between 1000-250 mb; 50 mb between 250-50 mb. First guess: Bilinear horizontal interpolation to observation point, vertical interpolation linear in ln p for u, v, q and T*, quadratic in ln p for heights. Satellite thickness profiles anchored to first-guess 1000 mb heights for quality control only, and then anchored to updated analysis.

Quality Control: Gross error for allowable magnitudes: q (15 g kg); multiple of standard deviations (Table 6). Flagged for questionable magnitudes (Table 6).

Buddy check is univariate within 832 km equal-area domain. Exclusion of flagged values if only 1 or 2 values in domain. Groups of ≥ 3: Calculate autocorrelations of first guess of each pair of values. Reports of observations are normalized by first-guess error std dev.

Toss if DFMAX > 3.5-2.5 FEC

1000m heights analysis: Univariate on 180 x 60 grid; 3-d data search of <16 reports. Search domain 1665km, except smaller if 10 reports exist

Mass and wind analysis: Along latitude circles; Observations within 1665 km. Up to 20 for profile reports, but no more than two levels of height and no more than one level of u and v from the same profile report

Numerical model characteristics: Grid sizes/domains; Horizontal/vertical discretizations; Parameterizations of convective and large-scale precipitation; frictional processes

Tropical cyclone bogus: Describe specification of wind, pressure, temperature and moisture fields.

APPENDIX D

Australian Bureau of Meteorology Research Centre

Regional Data Assimilation System

System Title:	Regional Assimilation and Prognosis (RASP)	
Documentation:	Submitted to Monthly Weather Review (See attachments)	
Domain:	Operations -	Lambert Conformal Projection over region approximately 0^{o} to 60^{o}S, 90^{o} to175^{o}E
	Research -	Locatable anywhere on globe with choice of three projections (Lambert Conformal, Mercator and Polar Stereographic)
Horizontal Resolution:	Operations -	150 km analysis and model
	Research	- arbitary, with telescoping option
Vertical Resolution:	Operations -	11 analyis levels (50,100,150,200,250,300,400,500,700, 800,1000 hPa)
		- 16 Model sigma - levels (0.05, 0.10 0.15, 0.20, 0.25. 0.3. 0.4, 0.5, 0.6, 0.7, 0.78, 0.85, 0.9, 0.95, 0.98, 0.995
	Research	- 14 analysis levels (10,20,30,50,70 100,200,250,300,400,500,700,850, 1000 hPa)
		- ultimately, analysis to be performed on sigma-surfaces
		- up to 20 model sigma-levels, including sigma=0.01 and 4 extra levels below sigma=0.85
Coupling:	Geostrophic wind/mass on analysis increments only. Decouples gradually in tropics	
Analysis:	Operations -	univariate O-I (3-D wind, 2-D mass)

Research - multivariate O-I (3-D wind, and mass)

Characteristics Operations- only significant level wind radiosonde data. Moisture to 400 mb, univariate SCM analysis of dewpoint with anisotropic influence function

Research - all significant level data moisture as in operations

First guess error correlation:

Operations - gaussian profile (horizontal)

- function of lnp (vertical)

Research - as in operations

- in the tropics a velocity potential correlation function is introduced to provide divergent wind increments

Initialization: Operations- adiabatic non-linear vertical normal mode initialization

Research - diabatic non-linear normal mode initialization

Assimilation method: Operations - 6 hour intermittent

Research - 3 hourly intermittent, nudging of cumulus heating rates in tropics

Superpbservations: two or more reports of same type combined if within 150 km, Linear average taking into account reliabilities

- single level winds take into account, vertical separation of 25mb

Data Preparation Characteristics: Operations-all radiosonde data, mandatory and significant level

- GTS satellite temperature, profiles and precipitable water

- no land retrievals below 700mb

- aircraft wind reports

- GMS cloud drift winds, except near jet streams

- ship, buoy and manual surface bogus observations

- microwave retrievals

- land surface pressure within 1½ hrs. Others within 3 hrs.

Research

- as in operations

- locally retrieved TOVS

- moisture bogus profiles based on GMS cloud imagery

Quality Control:

1. gross error check for allowable magnitudes. Threshold values for dewpoint depression, multiples of standard deviations for other fields. Reject, flag as doubtful, or pass.

2. buddy check. No buddy check on moisture. Others: doubtful can be accepted, passed may be thrown out.

Data Cut-off Time: 2.5 hours after synoptic time

First guess Characteristics: 6 hours regional model forecast

First guess Error Standard Deviations:

- heights and wind error standard deviations are initially set up as functions of latitude and level. However, the wind first guess error standard deviations are then adjusted for geostrophic consistency with the height error between 90° and 30°. Between 30° and the equator, geostrophy is gradually relaxed.

Observed Corrections to First Guess:

- use standard levels

- first guess: bicubic horizontal; lnp vertical

- satellite data used as thickness

1000 mb Height Field:

- MSLP analysis performed and 1000 mb heights derived using 1st guess low level temperature

- select up to 20 points in subgrid of 600 km x 600 km

Mass and Wind Analysis:

Operations - one level at a time. Select all observations at the mandatory level. Calculate horizontal correlation function

- look for off-level data. Calculate vertical correlation function

Research - multivariate O-I, so use significant level data

Numerical Model Characteristics:

Operations - 150 km horizontal, 16 sigma levels

- semi-implicit time differencing

- second order energy conserving spatial differencing on C-grid

- physical parameterizations:

1. Stability-dependent surface layer

2. Mixing-length theory above layer

3. Surface heat budget with prognostic equation for surface temperature

4. Large scale precipitation

5. Modified Kuo cumulus convection

6. Shallow convection

7. Evaporation of falling precipitation

8. Horizontal diffusion

Research - optional horizontal resolution, telescoping option

- upto 20 sigma levels

- split semi-lagrangian scheme on A-grid

- physical parameterizations:

1. Monin - Obukhov similarity theory in surface layer

2. Level 2.5 scheme in PBL

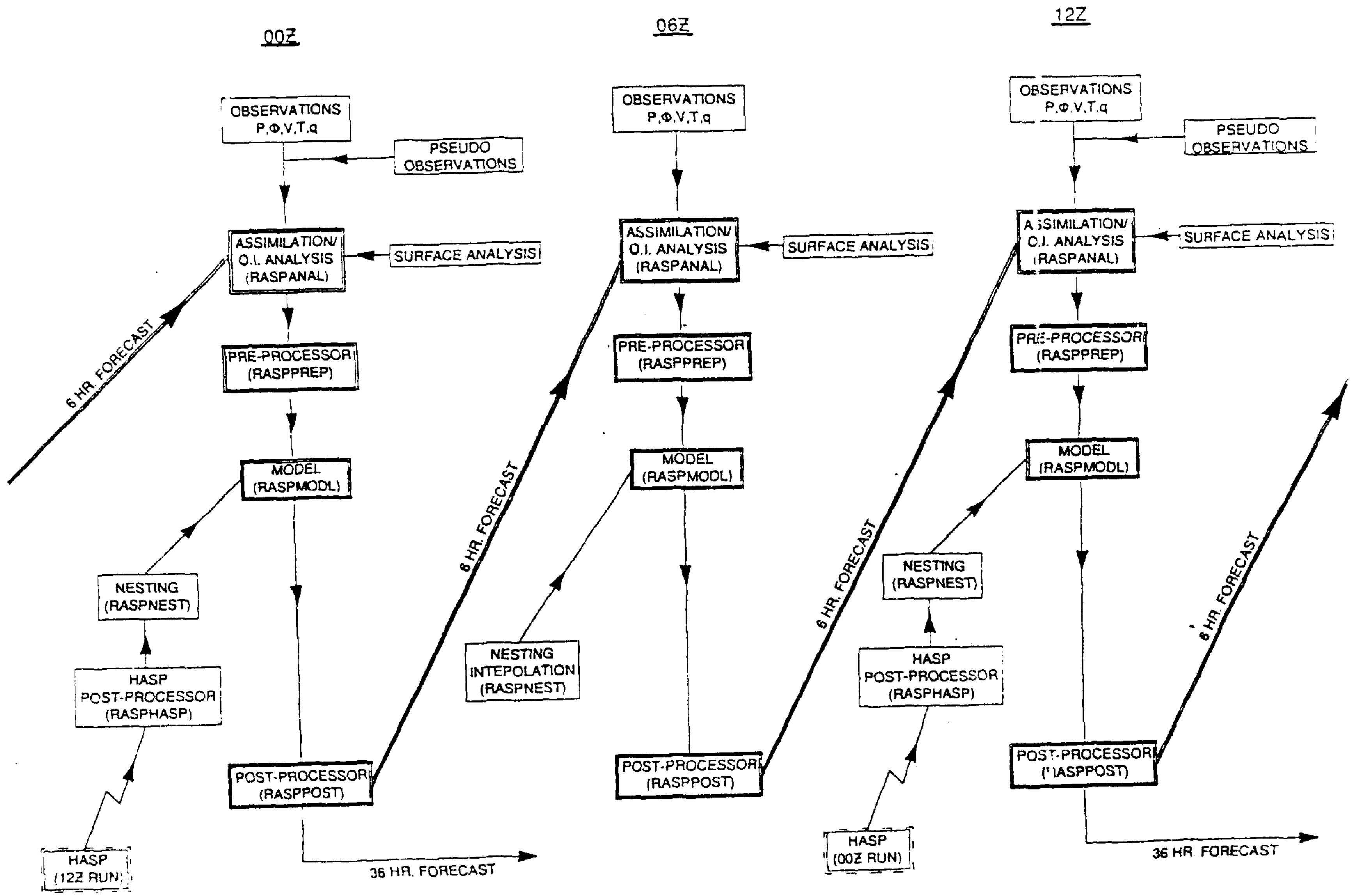
3. -8. as for operations except full radiation scheme available

<u>Tropical Cyclone Bogus</u>: Operations - surface PAOBS only

Research - a variety of schemes, being tested

<u>New data Sources</u>: e.g. Wind profilers - need to establish error characteristics etc.

SCHEMATIC REPRESENTATION OF THE REGIONAL ASSIMILATION AND PROGNOSIS (RASP) SYSTEM



APPENDIX E

A brief description of Global Analysis and Forecast System
in Japan Meteorologocal Agency

Atsushi Baba
Nemerical Prediction Division
Japan Meteorological Agency

System Title :

Global Analysis and Forecast System

Published Description :

K.Kashiwagi, 1987: On the impact of Space-based Observing Systems in the JMA Global Forecast/Analysis System. J.Meteor.Soc.Japan, 65,189-220

T.kitade, 1988: Numerical Weather Prediction in Japan Meteorological Agency. JMA/NPD Technical Report No.20

M.Ueno, 1989: Operational Bogussing and Numerical Prediction of Typhoon in JMA JMA/NPD Technical Report No.28

Domain :

Global

Horisontal Resolution(s) :

Analysis 192x97 1.875° long., lat.

Model Triangular truncation at wavenumber 63
(192 longitude and 96 Gaussian latitude)

Vertical Resolution(s) :

Analysis 16 levels (isobaric surfaces)
P = surface, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 10hpa

Model 16 levels (sigma layers)
σ_p= 995, 980, 950, 890, 800, 690, 565, 450, 360, 280, 210, 155, 110, 75, 45, 15hpa
Increment method is used for conversion of analysed P level data to Model's sigma level data.

Coupling :

Geostrophic wind/height coupling is applied with latitude(ϕ) dependent in the upper levels.

$\lvert\phi\rvert \leq 15°$	the coupling is not applied
$15° < \lvert\phi\rvert \leq 25°$	the coupling correlation are multiplied by an empilical coefficient which depends on latitude to gradually decouple the wind and height analysis.
$25° < \lvert\phi\rvert$	the coupling is applied

Analysis :

Tropsphere (850-100hpa)

Muitivariate OI in geopotential(h) and wind(u, v).

up to 30 observed values in the first analysis level(850hpa)

Moisture (relative humidity at surface-300hpa levels) is univariate.

(10 values max)

up to 42 observed values at upper levels

Stratosphere (70-10hpa)

Two dimensional least squares fitting method

Characteristics :

Mandatory pressure level radiosonde data are used

Significant level data are used for the vertical consistency checks.

Moisture vertical profiles are smoothed using both mandatory and significant level data.

First guess error correlation :

Horizontal correlation function

Homogeneity and isotropy are assumed for geopotential, temperature and moisture.

$\mu_{x_i x_j} = \exp(-br^2_{ij})$ for height and temperature where b is a constant which depends on variable(see figure 1(a)), level and latitude, r_{ij} is the distance between point i and j.

$\mu_{x_i x_j} = 1.0/(1.0+br^2_{ij})$ for moisture where b is a constant($b=1\sim4\times10^{-5}$).

r_{ij} is the distance between point i and j.

Vertical correlation function

see table 1

Initialization :

Nonlinear normal mode initialization with physics.

Super Observations :

Geopotential(h), wind(u, v), and temperature(t)

If two (or more) reports of the same type are located within a specified distance, most reliable data is selected considering data type and observation time. The specified distance is 50km for the surface data and AIREP and SATOB(satellite cloud draft winds) data. That for SATEM is 200km. SATEMs within 200km of TEMPs are not used.

Surface moisture data(relative humidity)

Two or more reports combined if 0.5° <lat., long. Linear average of location and observation values.

Data Preparation characteristics :

* Daytime shortwave radiation correction is applied for mandatory levels (height, temperature) from 150hpa on up.
* Moisture profiles of radiosonde observations are smoothed using both mandatory level data and significant level data.
* Satellite thicknesses are converted into temperatures at the analysis levels using a cubic spline; they are also converted into geopotential height. In order to reduce the biases caused by the rather strong vertical correlation of their observational errors, following procedure is used. First, we calculate the thickness between two analysis levels from the SATEM data. Next, we add this thickness to the value of the analysed geopotential height from the level below to give the height at the next level.
* Microwave data or low reliability data of satellite thickness data are used. The observation error of them are 2 times of heigh reliability ones.
* Moisture profiles based on GMS cloud data are used. (perhaps it corresponds to Moisture bogus profiles of NMC)
* SATOBs (Satellite cloud draft winds) at low levels (900hpa$\leqq$ p $\leqq$650hpa) are assigned to the 850hpa level and at high levels (350hpa$\leqq$ p $\leqq$70hpa) are assigned to the 200hpa level.
* Data observed within 3h of analysis time are used.

Data cutoff time :

6h after synoptic time

First guess characteristics :

6-h forecast of Global Spectrum model. (See Numerical model Characteristics)
(Global Data Assimilation System)

Quality Control :

* Check of code form
  If the form errors are found, some processes are carried out to recover the apparent errors and to extract the maximum information. In the case of TEMP part A, the flags of form errors are recorded to the decoded data.
* Check of duplicated data
  Duplicated reports are removed or edited according to the reception times, incoming communication lines and contents of the reports.

* Vertical consistency check

  It is performed for TEMP or PILOT data using Part-A,B,C,D and surface observations. The items of the Check are

  - Icing of instrument
  - Temperature lapse rate
  - Hydrostatic relationship
  - Consistency between the data at mandatory level and those at significant level
  - Consistency between the data at the lowest level and surface data
  - vertical wind shear

  For SATEM data, check of lapse rate is performed using the mean virtual temperature calculated from the thickness.

* Gross error check

  $D = |F^p - F^o|$ F^o; observation, F^p; First guess

  $D \geqq C1$ reject

  $D \leqq C2$ pass

  $C2 < D < C2$ to horisontal check

  $C1 = 4\sigma \sim 5\sigma$

  $C2 = 2\sigma \sim 3\sigma$

  σ : standard deviation of observation error(see figure 1(b))

* Horizontal check

  A simple two-dimensional nui-variate correction metod is used for the intepolating neighbouring data to the location of the data. If the difference between the data and the interpolated one is greater than a tolerance value, it is rejected.

Surface and 1000hpa heights analysis :

Univariate OI method is used. Search domain is 1665km, except smaller if 30 observations exist.

Now we only calculate 1000hpa geopotential height usng analysed surface pressure field.

Mass and wind analysis :

Observations within 1665km.

Observation error correlation

SATEMs ; $\mu_{ij} = \exp(-11.3 \times 10^{-6} r_{ij})$

r_{ij} : distance(km) between the two points

Others ; Horizontal error correlations : None

Vertical error correlation : see table 2

Numerical model characteristics :

* Integration domain Globe
* Horizontal Resolution Triangular truncation at wavenumber 63
* Grid 192 longitude and 96 Gaussian latitude
* Vertical levels 16 (sigma coordinate)
* Time integration Semi-implicit scheme
* Orography Included. Small scale smoothed
* Earth surface Monthly averaged albedo, soil moisture, ice cover specified geographically.
* SST daily analysed value.
* Physical parameterization
  (1) Surface exchanges: Louis's scheme for surface fluxes and level 2 version of the closure model for vertical diffusion
  (2) Convection: Kuo's scheme and shallow convection
  (3) Latent heating: Condensation of water vapor
  (4) Mountain wave drag
  (5) Radiation: Long wave cooling and solar heating with effects of cloud. Dirnal variation included.
  (6) Soil temperature calculated using a force restore method.

Tropical cyclone bogus :

The bogus vortex is automatically produced based on the parameters (center position, central surface pressure and mean radius of 15m/s wind) which are manually analysed by the staff of Forecast Devision at JMA.
To define a vortex, geopotential height(z), mean-sea-level pressue and wind are provided at five levels(surface, 850, 700, 500, 400hpa) around the center.
The number of bogus data changes according to the cyclone size.

Assimilation of vogus vortex

* The bogus vortex is assimilated through two stages.
* 1st stage
  Using only the bogus data (No data quality control process)
  2-dimensional univariate OI
  Horizontal correlation is sharper than the normal analysis(16 times)
* 2nd satge
  Nomal analysis using the other data.
  The guess field is the analysed one at the 1st stage.

Table 1 Coefficient of first guess error vertical correlation

1000	1.00									
850	0.60	1.00								
700	0.37	0.80	1.00							
500	-	0.48	0.75	1.00						
400	-	-	0.44	0.84	1.00					
300	-	-	-	0.47	0.78	1.00				
250	-	-	-	-	0.54	0.88	1.00			
200	-	-	-	-	-	0.53	0.82	1.00		
150	-	-	-	-	-	-	0.54	0.80	1.00	
100	-	-	-	-	-	-	-	0.64	0.78	1.00
	1000	850	700	500	400	300	250	200	150	100

Table 2 Coefficient of observation error vertical correlation

1000	1.00									
850	0.66	1.00								
700	0.40	0.81	1.00							
500	-	0.54	0.78	1.00						
400	-	-	0.65	0.88	1.00					
300	-	-	-	0.78	0.88	1.00				
250	-	-	-	-	0.78	0.89	1.00			
200	-	-	-	-	-	0.77	0.90	1.00		
150	-	-	-	-	-	-	0.81	0.93	1.00	
100	-	-	-	-	-	-	-	0.80	0.88	1.00
	1000	850	700	500	400	300	250	200	150	100

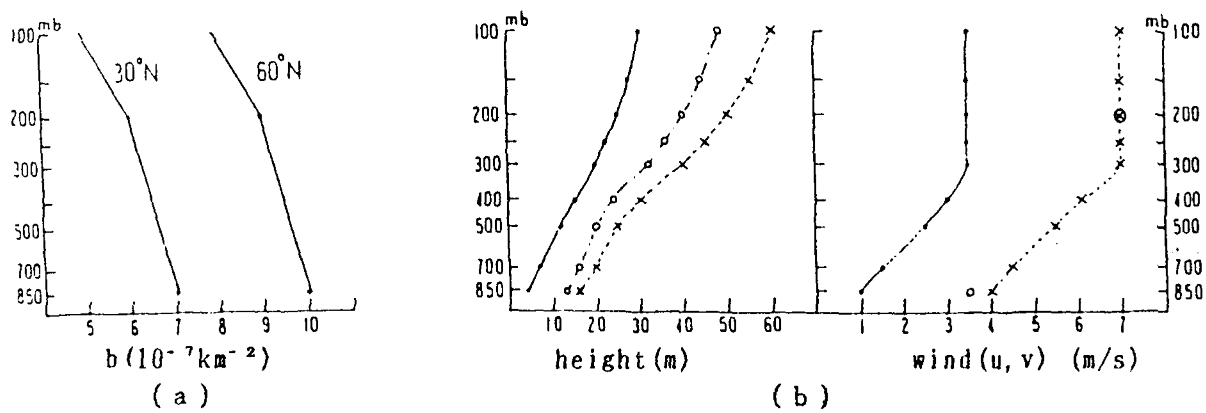


Figure 1 (a) Coefficient of first guess error correlation
(b) Observation and first guess error standard deviation
●—● sonde observation
×—× first guess
○—○ satellite observation

APPENDIX F

System Title: Navy Operational Global Atmospheric Prediction System (NOGAPS)

Published Description: In preparation.

Domain: Global

Horizontal Resolution: 1.5 degree resolution - analysis is performed for the 79 wave (triangular truncation) spectral model's Gaussian grid.

Vertical Resolution: Analysis - 16 levels (1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10)
Forecast Model - 18 layers whose centers are at approximately 1007, 991, 962, 916, 850, 770, 679, 583, 488, 399, 319, 251, 191, 138, 94, 58, 29, and 9.

Coupling: Geostrophic wind/mass (outside tropics). In tropics the geostrophic constraint is relaxed and the divergence is permitted to be non-zero (Daley, 1985).

Analysis: Multivariate OI in geopotential height and wind. Volume method similar to that developed by Lorenc (1981) with a maximum of 360 observations allowed per volume. Average number of observations used per volume is about 300. Analysis performed for deviations between observations and background (first-guess).

Characteristics: Significant level radiosonde data used for 925 mb level. Satellite soundings used as thicknesses between analysis levels. Operational bogusing of extra-tropical cyclones. Cloud-track winds, aircraft winds, pibals, and ship and buoy winds fully utilized. Surface observations of sea-level pressure converted to 1000 mb height. Surface observations of 850 mb height and 700 mb height utilized. Australian bogus observations utilized with adjusted observational error.

First-guess error correlation: Horizontal correlation function is damped cosine which best fits observed correlations computed using differences between background and North American radiosondes. Vertical correlation function is exponential in height and is determined using the aforementioned differences.

Initialization: Adiabatic nonlinear normal mode intialization with the operational spectral forecast model.

Super Observations: Not utilized. Data density is accounted for in the selection of data for each analysis volume and in the determination of the analysis volumes themselves.

Data Preparation Characteristics: All radiosonde data has extensive internal consistency checks performed for both height and winds using quality control procedures patterned after those used at ECMWF. Standard level data used with significant level data interpolated to produce 925 mb data. No correction made for radiation at present. Observations from hour of analysis used.

Satellite temperature soundings from NOAA-10, NOAA-11, DMSP F8, and DMSP F9 used for -3 to +3 hour time window surrounding analysis time. Soundings used as layer thicknesses between analysis levels. Observational error varies based upon instrument type, whether sounding is clear, partly cloudy, or cloudy, and upon time difference from analysis time. Over land areas only thicknesses above 500 mb are used. Over land areas rich in conventional data only thicknesses above 250 mb are used.

Aircraft and cloud-track winds used for -3 to +3 hour time window surrounding analysis time. Correction to wind speed applied to cloud-track winds above 600 mb with speeds greater than 20 m/sec.

Pibal and surface land reports used for analysis hour. Ship and buoy reports used for -3 to +3 hour time window surrounding anlysis time. Australian and FNOC bogus observations used.

For each analysis volume data are selected to ensure the "proper" mix of observational types and a uniform distribution in space of the observations.

Data cutoff time: 9 hours for 00Z and 12Z analyses, 3 hours for 06Z and 18Z analyses.

Background or first-guess characteristics: Global spectral model 6-hour forecast.

Background or first-guess error properties: For data-rich areas the wind error standard deviations are assumed to be constant over the globe. The height error standard deviations are derived via the geostrophic covariance model outside the tropics. In the tropics the height error standard deviation is held constant. In data-poor areas the error standard deviations are 1.6 times their values in the data-rich areas. The values used for height and wind error standard deviations have been found to agree quite well with those computed from the differences between radiosonde observations and the background fields.

Interpolation of first-guess to observation locations: Bicubic horizontal interpolation due to study by Franke (1985) which showed bilinear interpolation can result in significant errors.

Analysis quality control: Gross reject of observations whose difference from the background is more than 5 times the expected standard deviation. Final quality control is performed within the analysis itself for observations flagged as suspicious during the pre-analysis quality control or for observations whose difference from the background is 3 to 5 times the expected value. Following Lorenc (1981) these observations are examined by systematically removing their effect from the analysis and are eliminated when their effect upon the analysis is unreasonably large.

Numerical model characteristics: T79L18 Global Spectral Model with non-linear normal mode initialization, semi-implicit time differencing and implicit zonal advection of vorticity and moisture, gravity wave drag, silhouette orography, stable precipitation, and parameterization of shallow cumulus and the following diabatic processes:

PBL (Louis)
- Mixing coefficients (similarity theory)
- Ground temperature prediction

Radiation (NASA-Goddard)
- Fractional cloudiness
- Diurnal cycle
- Ozone heating

Cumulus (Arakawa-Schubert)
- New design
- Evaporation of falling precipitation
- Completely vectorized

Tropical cyclone bogus: Will be tested Fall or Winter 1989. Bogus will consist of wind observations surrounding the location of the tropical storm from 1000 mb up to 500 mb. Assimilation accomplished by OI analysis. Effect of mean flow considered in generation of bogus observations.

APPENDIX G

System Title: CIMSS Sub-Synoptic Model (SSM) Assimilation System

Published Description:

Analysis I: Seaman, R. S., R. L. Falconer, and J. Brown, 1977: Application of a variational blending technique to numerical analysis in the Australian region. Aust. Meteor. Mag., 25, 3-23.

Analysis II: User's Guide for Univariate Optimal Interpolation Analysis system is under development

Model: Leslie, L. M., G. A. Mills, L. W. Logan, D. J. Gauntlett, G. A. Kelly, M. J. Manton, J. L. McGregor and J. M. Sardie, 1985: A high resolution primitive equations model for operations and research. Aust. Meteor. Mag., 33,11-35.

Domain: Limited Area, relocatable, Lambert conformal

Horizontal Resolution: Analysis and Model - user defined, machine constrained (65x65X19 on IBM 4381), 150km - 30km grid spacing. Larger grid available on CYBER 930

Vertical Resolution:
Analysis I; 19 levels, 50mb spacing
Analysis II; 10 mandatory levels
Model; User specified sigma levels (19)

Coupling: Variational blending of optional velocity components (gradient, geostrophic, non-divergent or real winds) with geopotential

Analysis I: Successive correction with variational blending

Characteristics: Significant and manditory RAOBs, hourly surface data, TOVS temperature and moisture retrievals, VAS or SSMI precipitable water retrievals are analyzed on independent levels followed by vertical coupling through variational blending

Analysis II: Incremental analysis, using univariate OI or optional successive corrections

Characteristics: Incremental OI analysis of MSL pressure, geopotential, winds, temperature, and dewpoints. Analysis of wind increments is explicitly 3D. The MSL pressure increments influence the thickness guess fields via a vertical correlation function of geopotential. Thickness increment analysis are 2D. Geopotential and wind increments influence each other either by variational analysis or by geostrophic correction and are gradually decoupled with decreasing latitude.

Initialization: Vertical normal mode (Bourke and McGregor, 1983)

Super Observations: Constructed within limiting radius; MSL pressure, SATEM and SATOB data.

Data Preparation Characteristics:
- Significant and manditory level RAOB data validated and merged onto 50mb levels
- TOVS T and q profiles treated as pseudoRAOBS
- VAS and SSM/I precipitable water retrievals assimilated using 1D profile adjustment technique
- Optional moisture bogus from cloud imagery
- Optional wind reports from aircraft winds
- Optional winds generated by cloud drift wind algorithm

Quality code assignment: Background field checks and neighborhood checks using statistical interpolation parameters describing the variances and correlation functions of background field errors and observational errors

Data cutoff time: User specified in 4D assimilation mode

First-guess characteristics: Typically, NMC Global analysis or forecast, NMC RAFS analysis or forecast, or previous a model forecast. Other analyses can be used.

Wind errors: Optional checking against geostrophic and/or gradient winds

Quality control: Magnitude checks followed by subjective examination of final analysis field

Numerical model characteristics:

Grid sizes:	Optional (65X65), down to 35km
Domain:	Relocatable
Horizontal structure:	Arakawa C grid
Vertical structure:	Sigma up to 19 levels
Temporal structure:	Semi-implicit, flux form
Parameterizations:	Vertical diffusion (Gerrity,1977 and Phillips,1979)
	Modified Kuo convection (Kuo,1965)
	Large scale precipitation with evaporation (Philips,1979)
	Stability dependent bulk PBL with eddy diffusivities functions of bulk Richardson number
	Surface heat budget with prognostic equation for surface temperature

Tropical cyclone bogus: None

Advantages of CIMSS SSM Assimilation System

1. Uses variety of analyses/forecasts as a first-guess.

2. Access to satellite derived products via McIDAS, such as satwinds, integrated products (precipitable water, precip rates) from SSMI, TOVS retrievals, DMSP retrievals, SST composites...

3. Analysis can be easily configured to any location at any resolution.

4. 4D display capability using Stellar GS1000 computer with video tape production capability.

APPENDIX H-1 Model initialization method at GFDL/NOAA

Yoshio Kurihara

Data assimilation technique for a limited domain hurricane model has not been developed at GFDL. At present, data for the hurricane's environment are provided from a host model in which observations are assimilated. High resolution analysis of hurricanes will be separately made and it can be merged into the environmental condition.

An initialization technique has been developed at GFDL in order to initialize a hurricane model. It can also be used at initialization steps during the data assimilation process.

Domain: 55 degree longitude x 55 degree latitude (flexible)

Horizontal resolution: 1°, 1/3°, 1/6° (nested; flexible)
Sigma x 1000 = 995, 981, 960, 920, 856, 777, 688, 594, 497, 425, 375, 325, 275, 225, 175, 124, 74, 21 (13 levels below 250 mb).

Data base: NMC RAFS or GDAS, or ECMWF (all variables); Nested analysis (NRD/AOML) (wind, possibly mass field) Interpolation, bi-linear or smooth fitting (Akima), to the model grids from Gaussian grids.

Initialization: (a) static initialization, coupling by divergence equation (all terms included, bounded time tendency), (b) dynamic initialization, (c) moisture initialization.

Model characteristics: triply-nested movable mesh/18 levels/55 x 55 degree domain; high resolution (1/6°) topography; non-linear horizontal diffusion; Mellor-Yamada Level 2 vertical diffusion, background diffusion added; surface flux in Monin-Obukhov framework with interfacial layer included; large-scale condensation, moist convective adjustment including the entrainment effect; new forcing scheme at the open lateral boundary.

Some issues to be considered in the assimilation of tropical cyclone data are listed below:

1. Sufficiently high resolution is required to accurately analyze tropical cyclones. Large error in either or both of wind and mass fields can result from the data assimilation using a coarse resolution model.

2. The data assimilation method in the continuous data insertion mode should be tested. Also, variational methods, such as adjoint techniques, optimum nudging techniques, etc., may be applicable.

3. It is desirable to express the coupling between the wind and mass fields in a general form of divergence equation.

4. To initialize a model for the tropics, the time tendency may have to be taken into consideration. We should be concerned first with slow modes.

5. Schemes have to be developed to treat high resolution topography in the initialization process.

6. Problems of vortex spin-up are yet to be investigated.

(August 1989)

APPENDIX H-2

GFDL - DATA ASSIMILATION SYSTEM
(developed by Miyakoda, Stern and Ploshay)

Yoshio Kurihara

SYSTEM Four dimensional, continuous data insertion system

DOMAIN AND RESOLUTION

* domain	Global
* horizontal resolution	Analysis - N48 gaussian; Model - R42 (rhomboidal truncation at 42 waves)
* vertical resolution	Analysis - 19 pressure levels; Model - 18 levels (sigma x 1000 = 998, 980, 948, 901, 844, 777, 703, 624, 542, 458, 376, 297, 223, 156, 99, 52, 19, 2) (first 12 below 250 mb)

INSERTION DATA (Preprocessing)

* method	prepared by 3-dimensional, univariate, local optimum interpolation
* variables	P_{SL}, u, v, t, q on pressure levels
* grid	N48 gaussian, 19 pressure levels
* first guess	6 hour forecast
* data collection	500 km range, up to 12 obs.
* application	every 2 hours ($\pm$ 1 hour data window); time interpolation to fill in temporal gaps

ASSIMILATION

* cycle	6 hours
* method	continuous data insertion into a global spectral model; data updated every 2 hours
* variables	P_*, T, ζ (vorticity), D (divergence), q on sigma levels

INITIALIZATION

* method	incremental linear normal mode, 7 vertical modes (only modes with periods shorter than 6 hours adjusted)
* application	every timestep

MODEL CHARACTERISTICS

* resolution	R30L18 (rhomboidal truncation at 30 waves, 18 σ-levels)
* time integration	semi-implicit
* lateral diffusion	$K\nabla^2$
* vertical diffusion	Mellor-Yamada level 2.5; mountain-gravity wave drag; dry convective adjustment
* boundary layer	Monin-Obukhov process
* topography	spectrally truncated
* radiation	developed by Fels and Schwarzkopf (i) clouds - climatological monthly mean for each latitude (ii) application - diurnal variation; short- and long-wave radiation calculation every 2 hours
* sea surface temperature	RAND monthly climatological normals, yet varying daily
* land surface temperature	determined by surface heat balance, using 3 soil levels to model heat flux
* moisture	large scale condensation at 80% humidity saturation, cumulus parameterization by moist convective adjustment

(August 1989)

APPENDIX I

FSU PLANS FOR 4-DIMENSIONAL DATA ASSIMILATION FOR THE TROPICAL CYCLONE MOTION FIELD EXPERIMENT

(Selected cases only)

T.N. Krishnamurti

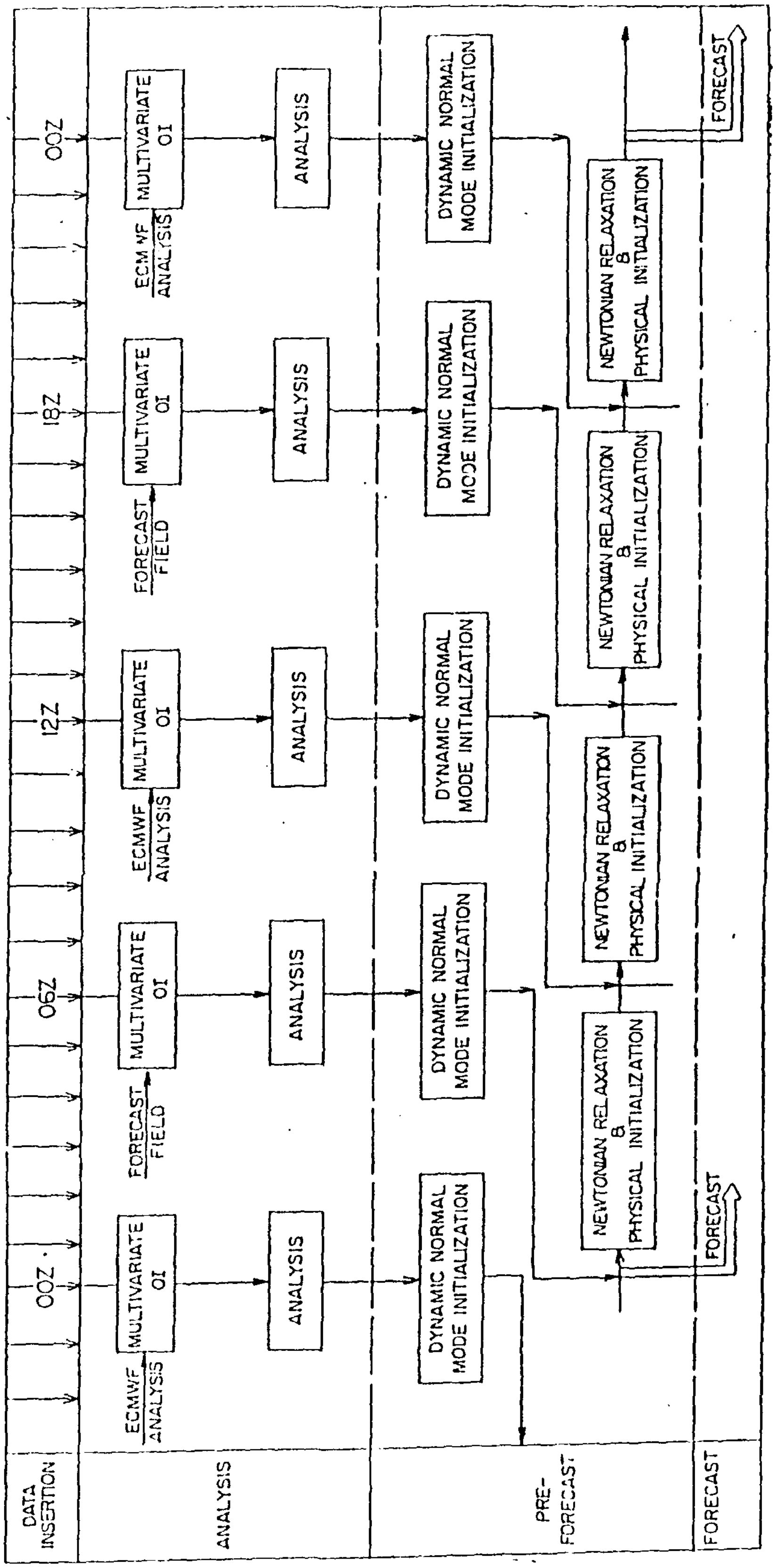
K.S. Yap

Gregg Rohaly

and

Jack Beven

FSU 4 - DIMENSIONAL DATA ASSIMILATION



DYNAMIC NORMAL MODE INITIALIZATION (SUGI,1986)

FORMULATION

(i) Split model equations into linear and non–linear terms

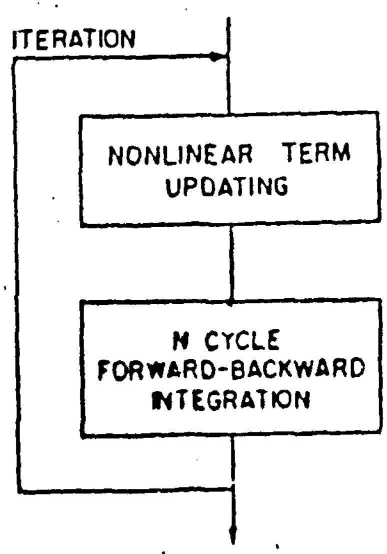
$$\frac{\partial X}{\partial t} = F_x^{\ell} + F_x^{n} \qquad X = u, v, P, \ln p_s$$

(ii) Obtain non–linear terms by integrating prediction model one time–step forward. Keep the terms fixed.

(iii) Integrate linear terms forward and backward N times using a frequency dependent selective damping time scheme.

(iv) Update non–linear terms and repeat time step (iii).

SCHEMATICALLY



(a) DNI

FSU LIMITED AREA NWP MODEL

Brief description

1. Primitive equation model
2. Vertical coordinate — σ (= p/p_s)
3. Number of vertical levels — 15
4. Horizontal staggering — Arakawa C grid
5. Boundary condition

   $\dot{\sigma} = 0$ at $\sigma = 1.0$ (earth's surface)

   $\dot{\sigma} = 0$ at $\sigma = 0.05$ (topmost level of model)
6. Time integration scheme — semi-implicit
7. Advection scheme — semi-Lagrangian
8. Physical processes — Full Physics

PHYSICAL PROCESSES

1. Parameterization of deep cumulus convection (Kuo, 1974; Krishnamurti *et al.*, 1983).
2. Stable heating following Krishnamurti (1986).
3. Supersaturation.
4. Parameterization of shallow convection (Tiedke, 1984).
5. Long and shortwave radiation (UCLA/GLAS GCM version).
6. Surface energy balance.
7. Surface fluxes via similarity theory.
8. Parameterization of ground wetness.
9. Orography.
10. Vertical diffusion following K theory.
11. Fourth order horizontal diffusion.

	$\sigma_1 = 0.050$	$P_1, \dot{\sigma}_1, z_1$
u_1, v_1, T_1, q_1		$\tilde{\sigma}_1$
	$\sigma_2 = 0.125$	$P_2, \dot{\sigma}_2, z_2$
u_2, v_2, T_2, q_2		$\tilde{\sigma}_2$
	$\sigma_3 = 0.175$	$P_3, \dot{\sigma}_3, z_3$
u_3, v_3, T_3, q_3		$\tilde{\sigma}_3$
	$\sigma_4 = 0.225$	$P_4, \dot{\sigma}_4, z_4$
u_4, v_4, T_4, q_4		$\tilde{\sigma}_4$
	$\sigma_5 = 0.275$	P_5, σ_5, z_5
u_5, v_5, T_5, q_5		$\tilde{\sigma}_5$
	$\sigma_6 = 0.350$	$P_6, \dot{\sigma}_6, z_6$
u_6, v_6, T_6, q_6		$\tilde{\sigma}_6$
	$\sigma_7 = 0.450$	$P_7, \dot{\sigma}_7, z_7$
u_7, v_7, T_7, q_7		$\tilde{\sigma}_7$
	$\sigma_8 = 0.550$	$P_8, \dot{\sigma}_8, z_8$
u_8, v_8, T_8, q_8		$\tilde{\sigma}_8$
	$\sigma_9 = 0.650$	$P_9, \dot{\sigma}_9, z_9$
u_9, v_9, T_9, q_9		$\tilde{\sigma}_9$
	$\sigma_{10} = 0.750$	$P_{10}, \dot{\sigma}_{10}, z_{10}$
$u_{10}, v_{10}, T_{10}, q_{10}$		$\tilde{\sigma}_{10}$
	$\sigma_{11} = 0.800$	$P_{11}, \dot{\sigma}_{11}, z_{11}$
$u_{11}, v_{11}, T_{11}, q_{11}$		$\tilde{\sigma}_{11}$
	$\sigma_{12} = 0.850$	$P_{12}, \dot{\sigma}_{12}, z_{12}$
$u_{12}, v_{12}, T_{12}, q_{12}$		$\tilde{\sigma}_{12}$
	$\sigma_{13} = 0.900$	$P_{13}, \dot{\sigma}_{13}, z_{13}$
$u_{13}, v_{13}, T_{13}, q_{13}$		$\tilde{\sigma}_{13}$
	$\sigma_{14} = 0.950$	$P_{14}, \dot{\sigma}_{14}, z_{14}$
$u_{14}, v_{14}, T_{14}, q_{14}$		$\tilde{\sigma}_{14}$
	$\sigma_{15} = 0.990$	$P_{15}, \dot{\sigma}_{15}, z_{15}$
$u_{15}, v_{15}, T_{15}, q_{15}$		$\tilde{\sigma}_{15}$
	$\sigma_{16} = 0.000$	$P_{16}, \dot{\sigma}_{16}, z_{16}$

EXPLICIT NEWTONIAN RELAXATION

($A \equiv u, v, p_s$, (and q))

$$\frac{\partial A}{\partial t} = \text{------------} \; N\,(A^{\circ}(x,y,\sigma,t) - A\,(x,y,\sigma,t))$$

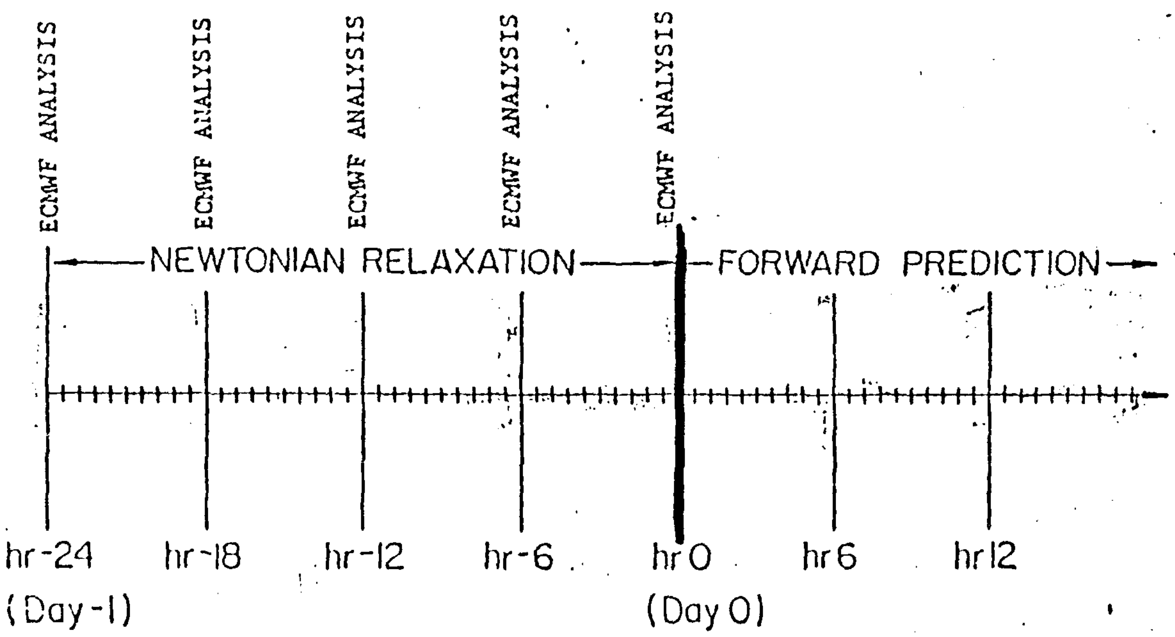


Figure 7a: Schematic outline of the explicit relaxation of u, v, p_s during the Newtonian relaxation phase.

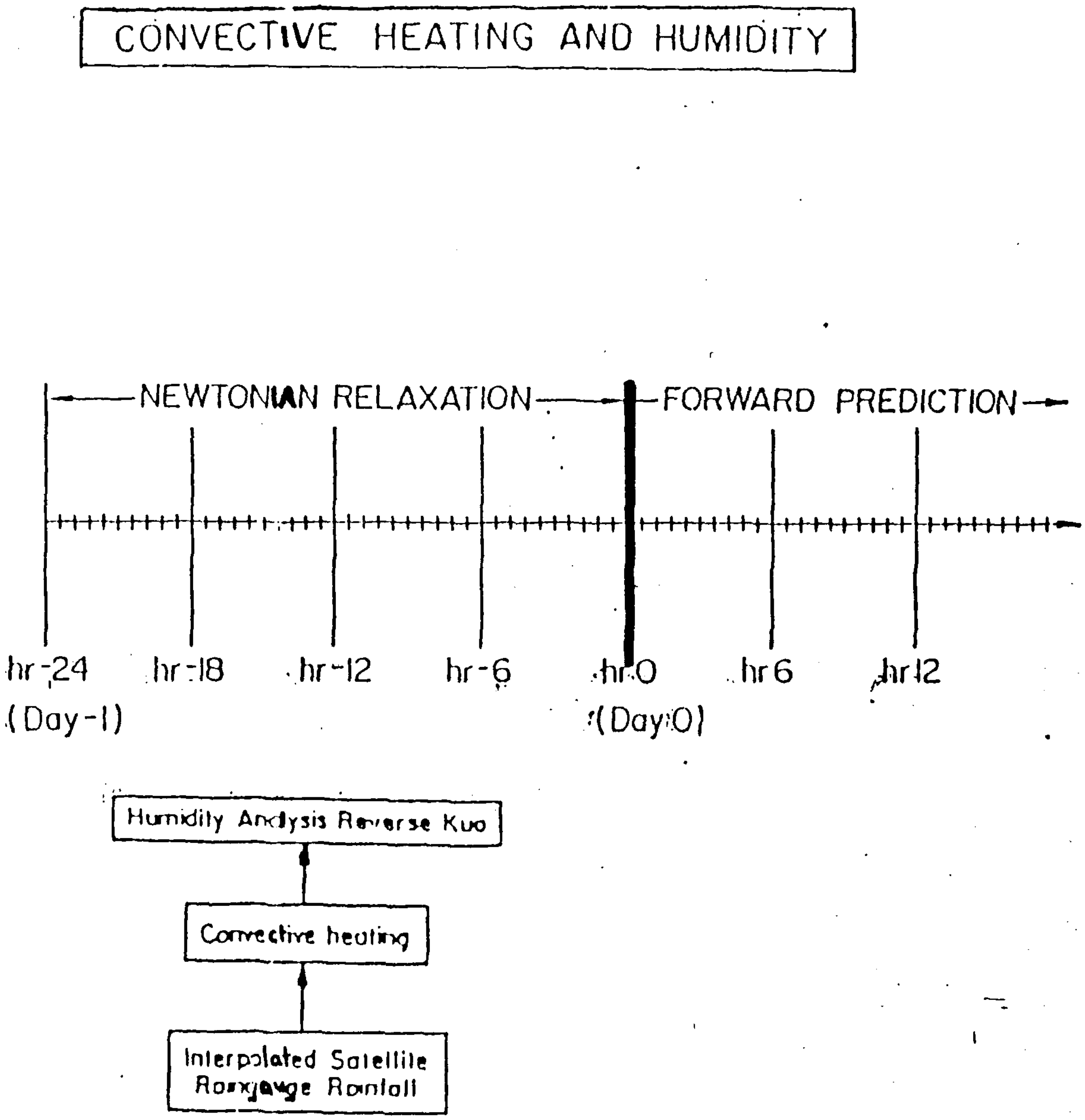


Figure 7b: Schematic outline of the implicit handling of humidity and convective heating. Here the Reverse Kuo algorithm is involved during each time-step of the Newtonian relaxation.

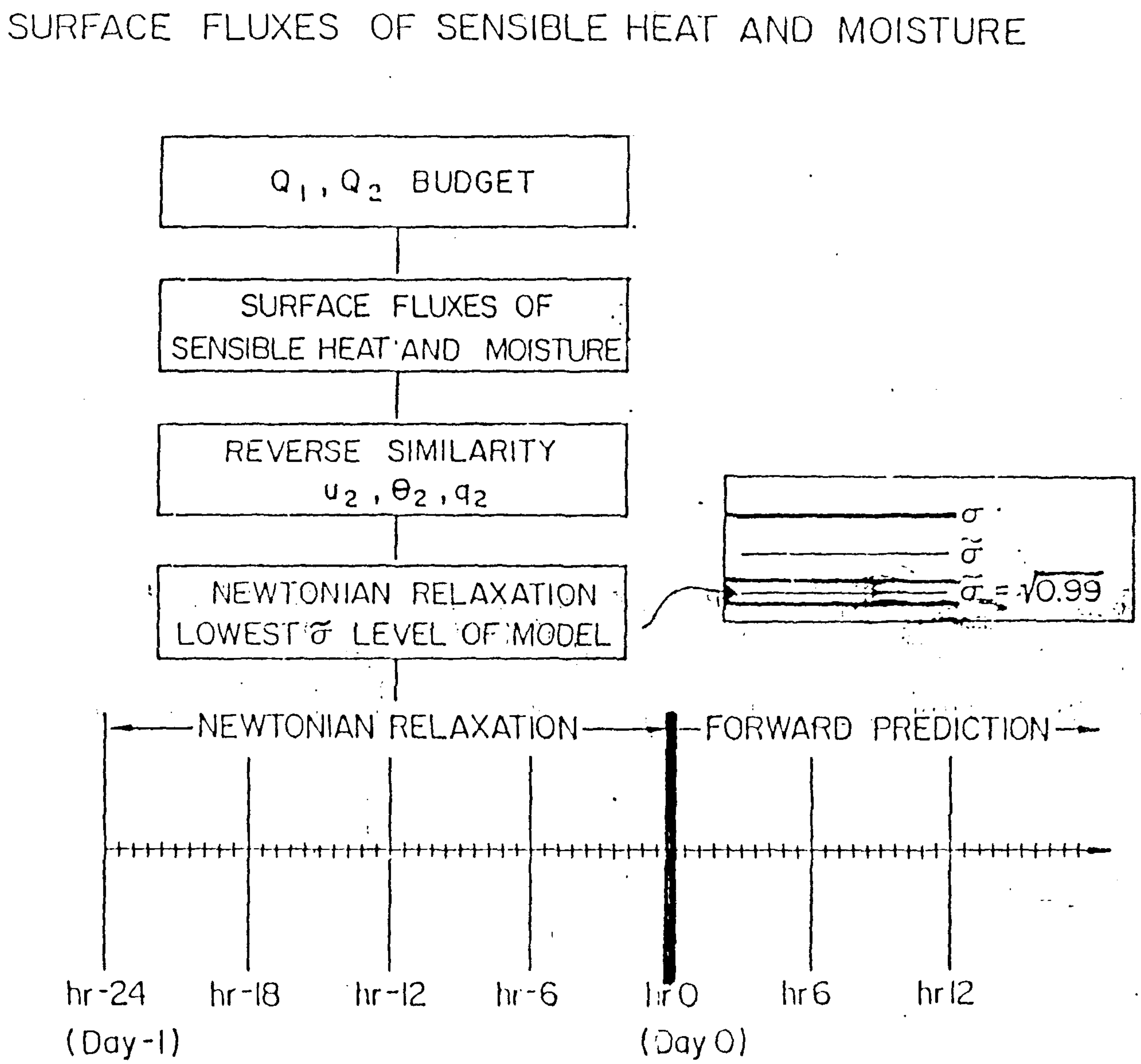


Figure 7c: Schematic outline of the implicit handling of surface fluxes of sensible heat and moisture. Here a reverse similarity algorithm is involved during each time-step of the Newtonian relaxation phase to give $\vec{V}$, θ, q at the lowest sigma level of the model. A Newtonian relaxation is then performed using these values.

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